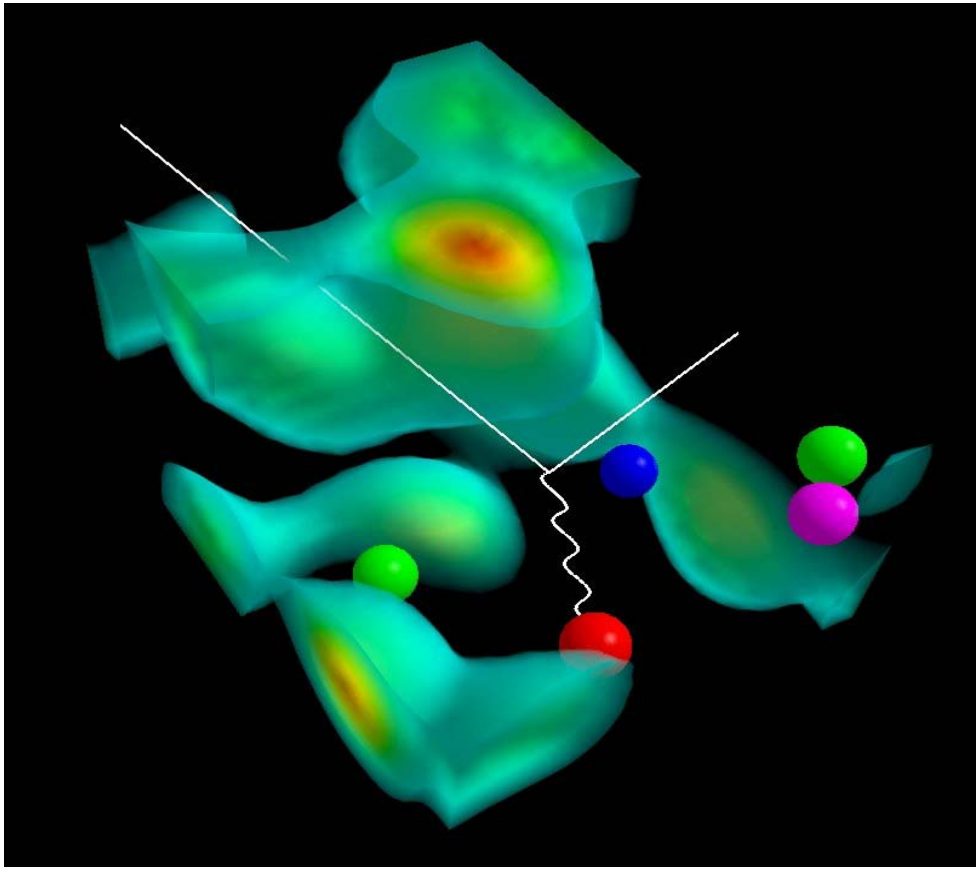
Orbital Angular Momentum and Nucleon Structure



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Anthony W. Thomas

Workshop on Orbital Angular Momentum in QCD
INT Seattle - February 9th 2012

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

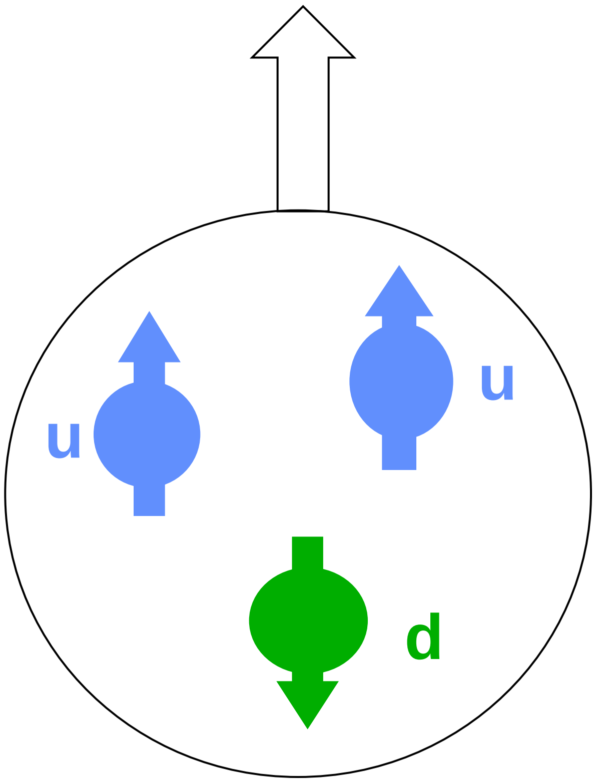
Outline

- A reminder: the proton "spin crisis" is *not* the same as the "spin problem": $L^q + S^q + J^g = 0.5$
- Progress driven/diverted by search for a huge value of $\Delta G \sim 4$ – eventually much smaller!
- The resolution of the problem
  - one-gluon-exchange
  - the pion cloud
  - input from lattice QCD

- QCD evolution essential to comparison with lattice data
- Future outlook : overcoming systematic errors in lattice QCD essential

What do we expect ?

Most quark models start with 3 quarks in the 1s-state of a confining potential: proton spin is ALL carried by its quarks: $\Sigma = 100\%$



N.B. Given low values of $m_{u,d}$ the quark motion is relativistic and lower Dirac components have spin down: $\Sigma \sim 65\%$

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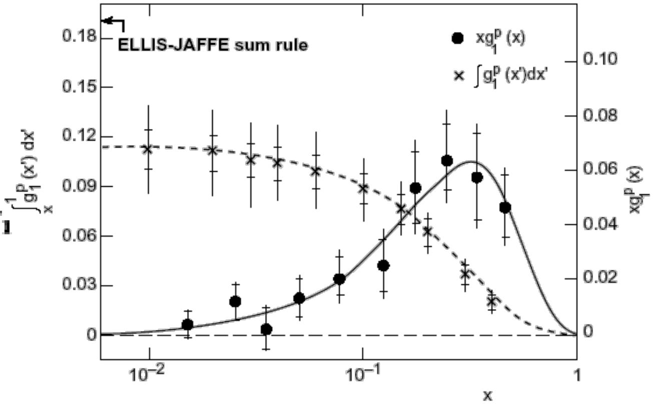
The Beginning

Volume 206, number 2 PHYSICS LETTERS B 19 May 1988



A MEASUREMENT OF THE SPIN ASYMMETRY AND DETERMINATION OF THE STRUCTURE FUNCTION g_1 IN DEEP INELASTIC MUON–PROTON SCATTERING

European Muon Collaboration

Aachen, CERN, Freiburg, Heidelberg, Lancaster, LAPP (Annecy), Liverpool, Marseille, Mons, Oxford, Rutherford, Sheffield, Turin, Uppsala, Warsaw, Wuppertal, Yale

J. ASHMAN [a], B. BADELEK [b,1], G. BAUM [c,2], J. BEAUFAYS [d], C.P. BEE [e], C BENCHOUK [f],

(93 authors)

The spin asymmetry in deep inelastic scattering of longitudinally polarised muons by longitudinally polarised protons has been measured over a large x range $(0.01 < x < 0.7)$. The spin-dependent structure function $g_1(x)$ for the proton has been determined and its integral over x found to be $0.114 \pm 0.012 \pm 0.026$, in disagreement with the Ellis–Jaffe sum rule. Assuming the validity of the Bjorken sum rule, this result implies a significant negative value for the integral of g_1 for the neutron. These values for the integrals of g_1 lead to the conclusion that the total quark spin constitutes a rather small fraction of the spin of the nucleon.

$\Sigma = 14 \pm 3 \pm 10$ % :

i.e. 86% of spin of p NOT carried by its quarks

and *possibly none*

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Ancient History of the Spin Crisis

- EMC Spin Paper: 22 Dec 87 - 19 May 88
- Schreiber-Thomas CBM: 17 May 88 - 8 Dec 88
- Myhrer-Thomas OGE: 13 June 88 - 1 Sept 88

(neither paper could explain reduction to only 14%!)

- Efremov-Teryaev Anomaly: 25 May 88
- Altarelli-Ross Anomaly: 29 June 88 - 29 Sept 88
- Carlitz, Collins, Mueller and many, many others…

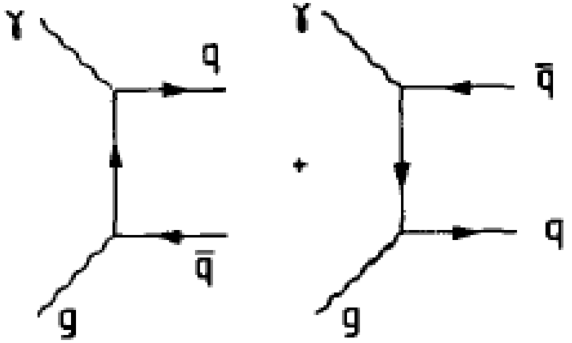
Possible Role of Polarized Glue in the Proton

$$\Sigma_{\text{naïve}} \rightarrow \Sigma_{\text{naïve}} - N_f\, \alpha_s\, \frac{(Q^2)\, \Delta G}{2\pi} (Q^2)$$

and

QCD evolution: $\alpha_s(Q^2)\, \Delta G(Q^2)$ does not vanish as $Q^2 \rightarrow \infty$

and polarized gluons would resolve crisis



Required ΔG ~ +4…. no physical explanation of such a huge value (8 times proton spin) offered !

This spurred a tremendous experimental effort

- DIS measurements of spin structure functions of polarized p, d, ^{3}He (and ^{6}Li) at SLAC, CERN, Hermes, JLab

- Direct search for high-p_T hadrons as well as inclusive jet and π^0 production at Hermes, COMPASS, RHIC to directly search for effects of polarized glue in the p

- This effort has lasted the past 25 years, with great success

Where is the Spin of the proton?

- Modern data (Hermes, COMPASS) yields:
  $\Sigma = 0.33 \pm 0.03 \pm 0.05$

  (c.f. $0.14 \pm 0.03 \pm 0.10$ originally)

- In addition, there is little or no polarized glue
  - COMPASS: $g^D_1 = 0$ to $x = 10^{-4}$
  - A_{LL} (π^0 and jets) at PHENIX & STAR: $\Delta G \sim 0$
  - Hermes, COMPASS and JLab: $\Delta G / G$ small

- Hence: axial anomaly plays at most a very small role in explaining the spin crisis

- Return to alternate explanation lost in 1988 in rush to explore the anomaly

Ancient History of the Spin Crisis

- EMC Spin Paper: 22 Dec 87 - 19 May 88
- Brodsky et al. Skyrme: 22 Feb 88 - 19 May 88
- Schreiber-Thomas CBM: 17 May 88 - 8 Dec 88
- Myhrer-Thomas OGE: 13 June 88 - 1 Sept 88

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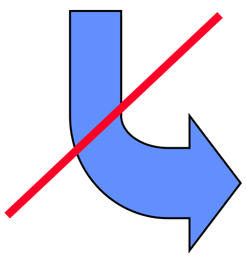


One-Gluon-Exchange Correction

PHYSICAL REVIEW D VOLUME 38, NUMBER 5 1 SEPTEMBER 1988

Rapid Communications

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no longer than 3½ printed pages and must be accompanied by an abstract. Page proofs are sent to authors, but, because of the accelerated schedule, publication is not delayed for receipt of corrections unless requested by the author or noted by the editor.

Spin structure functions and gluon exchange

F. Myhrer
Department of Physics and Astronomy, University of South Carolina, Columbia, South Carolina 29208

A. W. Thomas
*Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5000, Australia and Department of Theoretical Physics, Oxford University, Oxford OX1 3NP, Oxfordshire, England**

(Received 13 June 1988)

Two-quark correlations due to gluon exchange give corrections to both the proton and neutron spin-dependent structure functions in the Bjorken sum rule. They are found to be as large as the pionic corrections in the cloudy bag model of the nucleon. While still not enough to explain the result published recently by the European Muon Collaboration, it is compatible with the reanalysis of the data by Close and Roberts.

OGE Hyperfine Interaction

- **Essentially <u>every quark model needs this QCD based interaction for hadron spectroscopy</u> – beginning with de Rujula et al.; De Grand et al. ; Isgur & Karl……..**
- **N-Δ, Σ-Λ splitting etc…**
  (MIT bag, constituent quark model(s))
- **As soon as this is included one must also calculate the corresponding exchange current corrections**
- **First done for magnetic moments and non-singlet axial charges by Hogaasen and Myhrer**

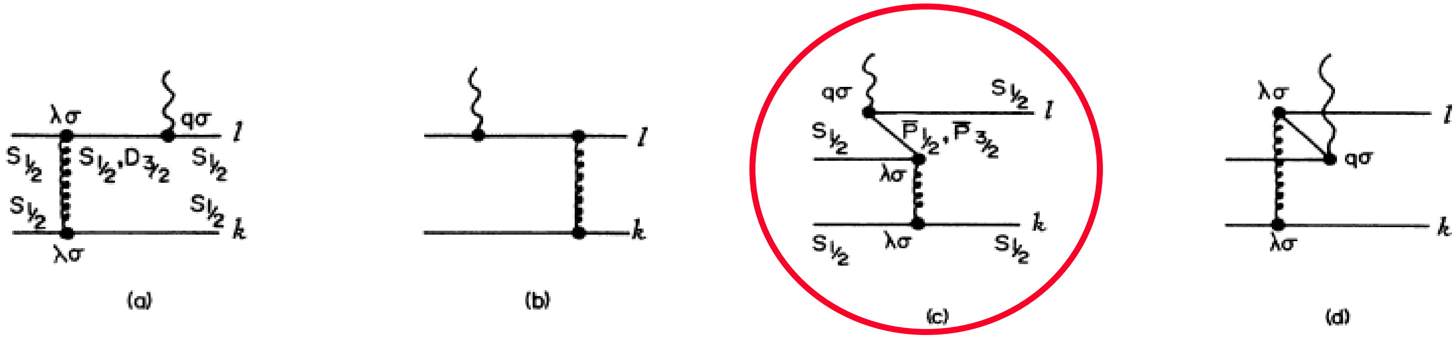
PHYSICAL REVIEW D VOLUME 37, NUMBER 7 1 APRIL 1988

SU(6) violations due to one-gluon exchange

H. Høgaasen
Fysisk Institutt, University of Oslo, Blindern, 0316 Oslo 3, Norway

F. Myhrer
Department of Physics, University of South Carolina, Columbia, South Carolina 29208
(Received 26 October 1987)

The one-gluon-exchange corrections to the baryon magnetic moments and the weak semileptonic decays are shown to have the correct two-body operator in order to explain recent data. An explicit model calculation using a mode sum for the quark propagator is then performed. In this model calculation the two lowest states dominate the corrections. This value of SU(6) breaking explains the measured ratio $\Sigma^- \to n e \bar{\nu} / \Lambda \to p e \bar{\nu}$ as well as why $\mu_{\Xi^-} < \mu_\Lambda$ and it restores $\mu_p/\mu_n \simeq -\frac{3}{2}$ in chiral bag models.



Intermediate quark state contributing M	Intermediate quark energy	$10^4\Delta\mu$	$10^4\Delta g_A$	Intermediate quark energy M	$10^4\Delta\mu$	$10^4\Delta g_A$
$S'_{1/2}$	$5.40/R$	22	32	$8.58/R$	1.0	2.2
$D_{3/2}$	$5.12/R$	8	12	$8.41/R$	0.4	0.8
$\bar{P}_{1/2}$	$3.81/R$	730	−275	$7.00/R$	−6.7	7.0
$\bar{P}_{3/2}$	$3.20/R$	1349	−332	$6.76/R$	−6.1	6.0
Sum		2109	−563		−11.4	16.0

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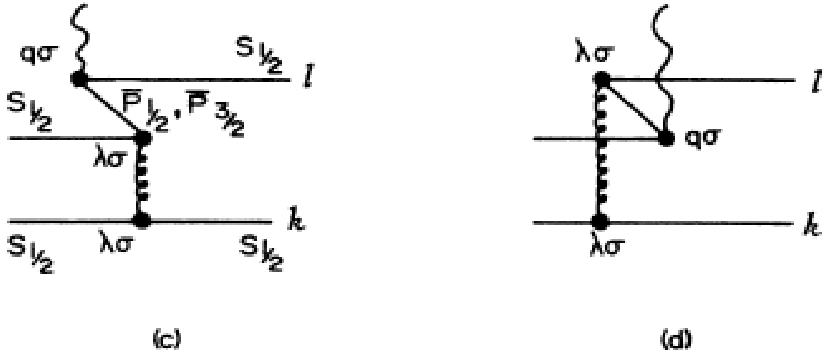
SUBATOMIC STRUCTURE OF MATTER

OGE Exchange Current : Spin Problem

- **Further reduces the fraction of spin carried by the quarks in the bag model (naively 0.65)**



$$\Sigma \rightarrow \Sigma - 3G \text{ ; with } G \sim 0.05$$
$$\Sigma \rightarrow 0.65 - 0.15 = 0.5$$

- **Effect is to transfer quark spin to quark (relativity) and anti-quark (OGE) orbital angular momentum**

Myhrer-Thomas, Phys Rev D38 (1988);
and most recent: Altenbuchinger et al., EPJ, arXiv:1012.4409

Chiral Symmetry

- The other critical issue in hadron structure which has come to the fore recently

- Cloudy bag model of Miller, Théberge and Thomas
  – naturally yields correct LNA and NLNA behaviour of baryon properties

- Chiral quark model of Georgi & Manohar, which doesn't

- Later χQSM etc....

The Pion Cloud of the Nucleon

Volume 215, number 1 PHYSICS LETTERS B 8 December 1988

SPIN DEPENDENT STRUCTURE FUNCTIONS IN THE CLOUDY BAG MODEL

A.W. SCHREIBER AND A.W. THOMAS

Department of Physics and Mathematical Physics, University of Adelaide,
North Terrace, Adelaide, South Australia 5000, Australia

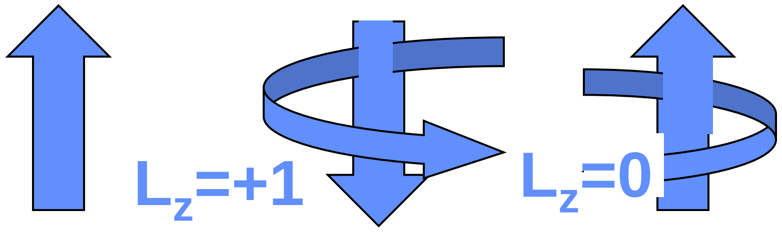
Received 17 May 1988

We derive expressions for the integrals of the spin dependent structure functions $g_1(x)$ for the proton and the neutron in the context of the cloudy bag model. We find that the neutron contributes 5–10% to the Bjorken sum rule, while there is a corresponding decrease for the proton's contribution. It is difficult to reconcile these results with those reported in a recent experiment.

Effect of the Pion Cloud

- Probability to find a bare N is Z ~ 70%

- Biggest Fock Component is N π ~ 20-25% and 2/3 of the time N spin points down



$Z \qquad \frac{2}{3} P_{N\pi} \qquad \frac{1}{3} P_{N\pi}$

- Next biggest is $\Delta\,\pi$ ~ 5-10%

- To this order (i.e. including terms which yield LNA and NLNA contributions):

- Spin gets renormalized by a factor :

$$Z - 1/3\, P_{N\pi} + 15/9\, P_{\Delta\pi} \sim 0.75 - 0.8$$

$$\text{Hence: } \Sigma = 0.65 \rightarrow 0.49 - 0.52$$

Schreiber-Thomas, Phys Lett B215 (1988)

Support for Pion Cloud Picture

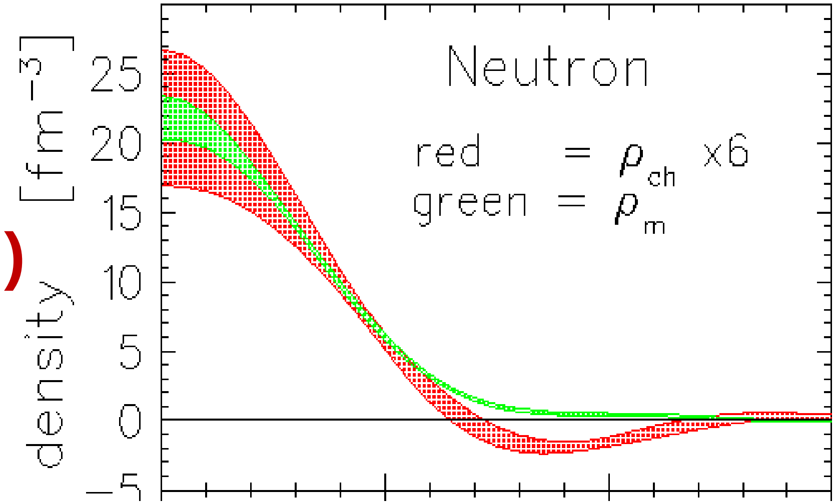
- **Most spectacular example is the <u>prediction</u>* of $\bar{d} > \bar{u}$, because of the pion cloud ($p \to n\,\pi^+$)**

$$\int_0^1 dx\,[\,\bar{d} - \bar{u}\,] = 2\,P_{N\pi}/3 - P_{\Delta\pi}/3$$

$$\varepsilon\ 0.11 - 0.15$$

(in excellent agreement with latest data)

J.J. Kelly



- **Charge distribution of the neutron (don't say it Jerry!)**

- **Natural understanding of quark mass dependence of data from lattice QCD**

* Thomas, Phys. Lett. B126 (1983) 97

Adding OGE and Pion Corrections

- **It's immediately apparent that combining these two corrections does not reproduce the EMC result**

- **BUT it got close: very nice study by**
  Yamaguchi, Tsushima, Kohyama and Kubodera, Nucl. Phys. A500 (1989) 429

  did this and included kaons too

- **Clearly the modern value of Σ will be described very well (.... discussed soon)**

BUT: Should one add OGE and Pion Corrections?

- **Prime phenomenological need for OGE interaction is the hyperfine splitting of hadron masses,**

- **In early days of chiral models believed some of this hyperfine splitting came from pion self-energy differences**

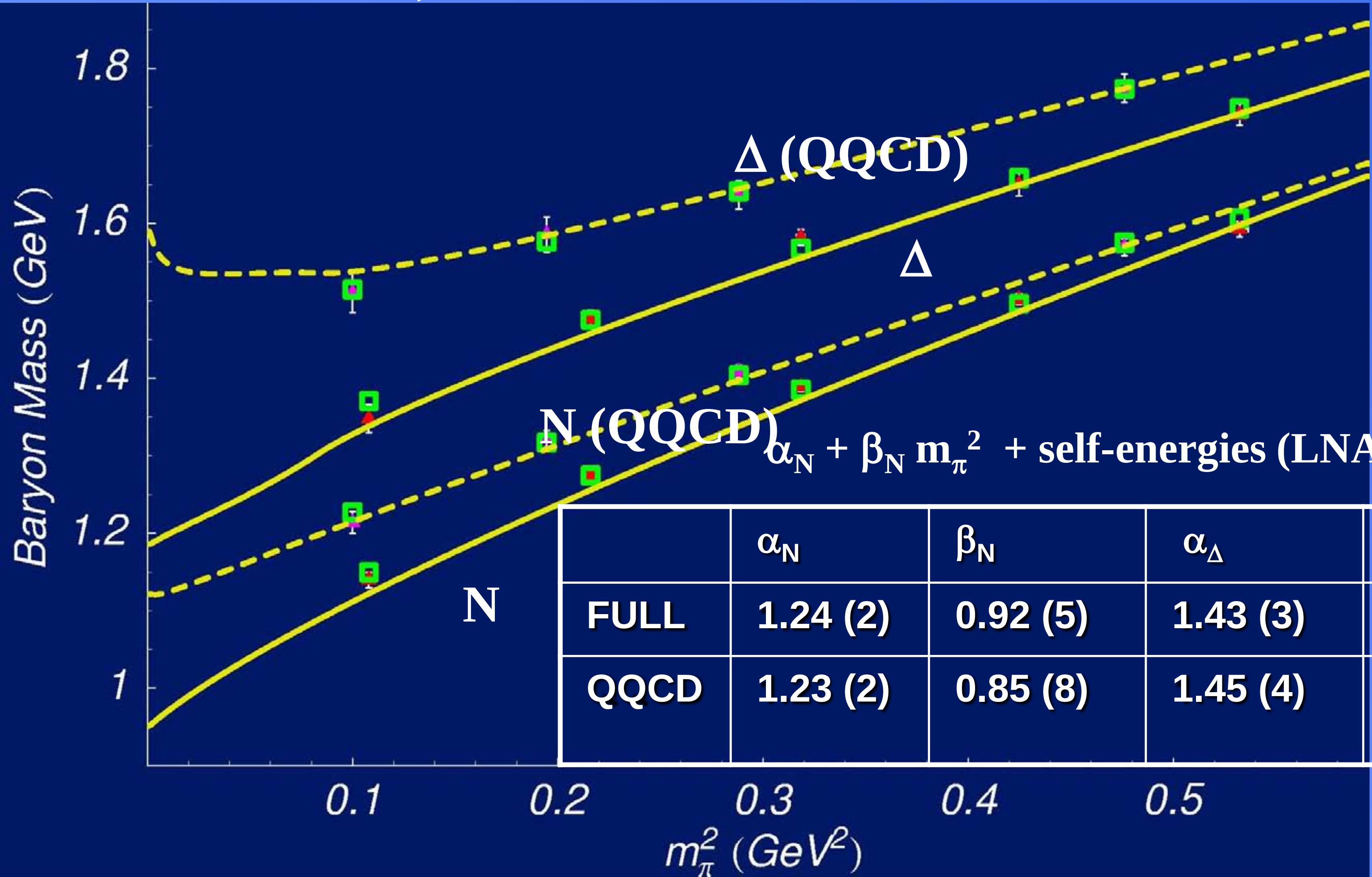
- **Maybe double counting to include correction to Σ from both pions and OGE??**

- **Modern understanding: *NO!* – from analysis of data in quenched (QQCD) and full QCD, from Lattice - implies 50 MeV (or less) of $m_\Delta - m_N$ in this way**

•

Young et al., Phys. Rev. D66 (2002) 094507

- Lattice data (from MILC Collaboration) : red triangles
- Green boxes: fit evaluating σ's on same finite grid as lattice
- Lines are exact, continuum results



$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

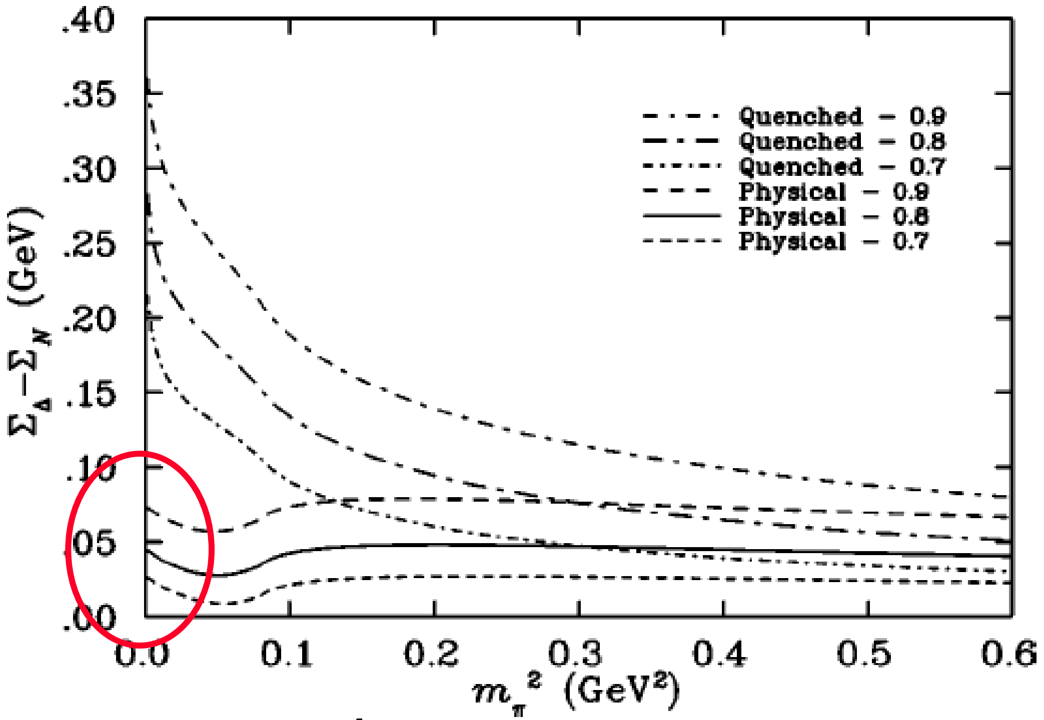
	α_N	β_N	α_Δ	β_Δ
FULL	1.24 (2)	0.92 (5)	1.43 (3)	0.75 (8)
QQCD	1.23 (2)	0.85 (8)	1.45 (4)	0.71 (11)

Young *et al.*, hep-lat/0111041; Phys. Rev. D66 (2002) 094507

Nucleon - Δ Splitting

Lattice analysis implies pions give 40 ± 20 MeV

PHYSICAL REVIEW D **66**, 094507 (2002)



- **Hence most of the N-Δ splitting comes from OGE – as in most quark models**

- **Thus the value of α_s used in the bag model calculation of the exchange current correction is more or less unchanged**

- **and… one can add the pion and OGE corrections without significant double counting**

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Final Result for Quark Spin

$\Sigma = (Z - P_{N\pi}/3 + 5\, P_{\Delta\pi}/3)\ (0.65 - 3\, G)$

$= (0.7,0.8)$ times $(0.65 - 0.15) = (0.35, 0.40)$

c.f. Experiment: 0.33 ± 0.03 ± 0.05

- ALL effects, relativity and OGE and the pion cloud

swap quark spin for valence orbital angular momentum

and anti-quark orbital angular momentum

(>60% of the spin of the proton)

Myhrer & Thomas, hep-ph/0709.4067

The Balance Sheet – fraction of total spin

	$2\,L_{u+ubar}$	$2\,L_{d+dbar}$	Σ
Non-relativistic			1.0
Relativity (e.g. Bag)	0.46	-0.11	0.65
Plus OGE	0.52	-0.02	0.50
Plus pion	0.50	0.12	0.38

At model scale: $L_u + S_u = 0.25 + 0.42 = 0.67 = J_u$

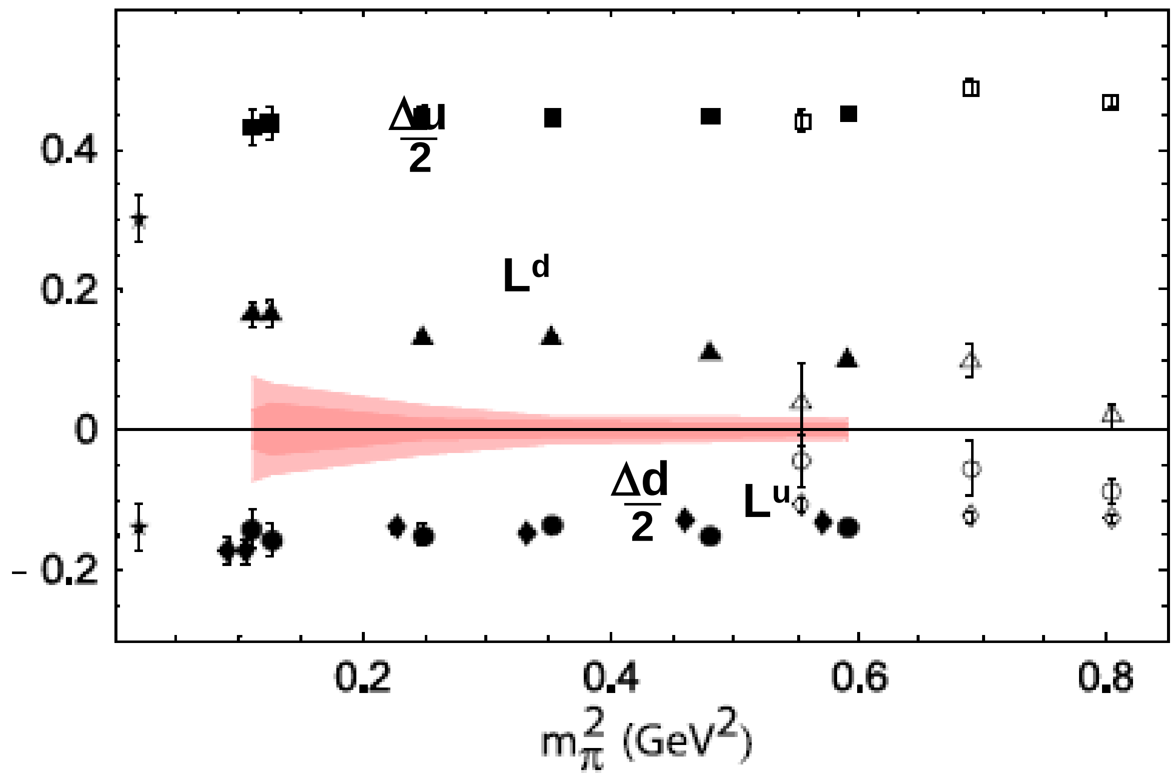
$: L_d + S_d = 0.06 - 0.22 = -0.16 = J_d$

Phys Rev Lett, 101 (2008) 102003

LHPC Lattice Results

- At first glance shocking :

$L^u \sim -0.1$ and $L^d \sim +0.1$
(c.f. + 0.25 and +0.06 in our "resolution")



LHPC: hep-lat/0610007

The key : J^q (L^q) is not scale invariant – what scale?

- Known since mid-70s (Le Yaouanc et al., Parisi, Bell, Jaffe...) that connection between quark models and QCD *must be* at a low scale

- This is because momentum fraction carried by quarks is monotonically decreasing with increasing Q^2
  - whereas: in models quarks carry all the momentum

- Used (for example) by Glück-Reya to model HERA data to 10^5 GeV^2, starting with valence dominated distributions (in LO) at $\mu^2 = 0.23$ GeV^2 (Phys Lett 359, 205 (1995))

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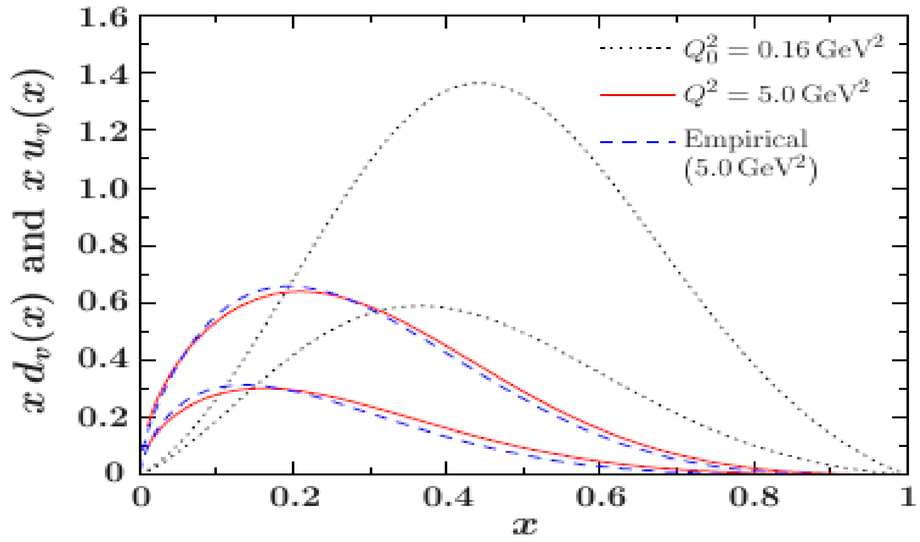
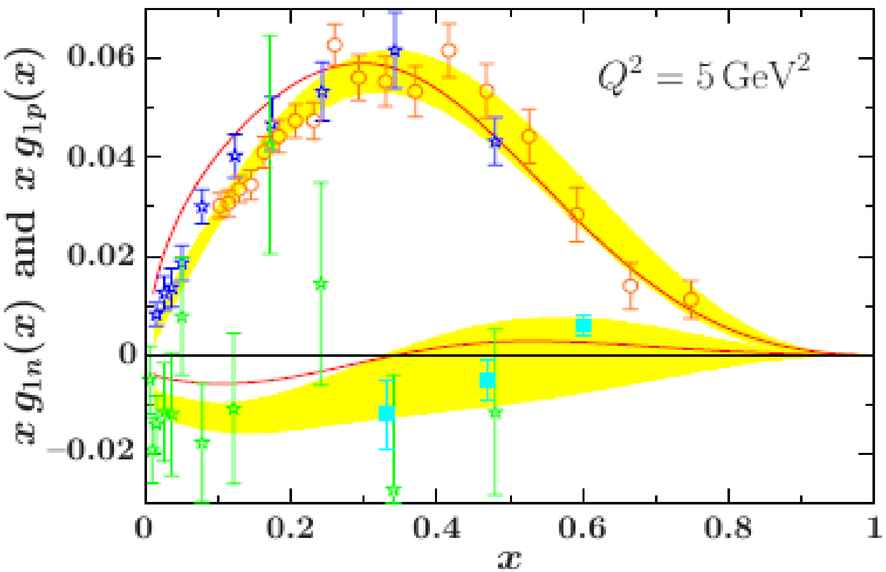
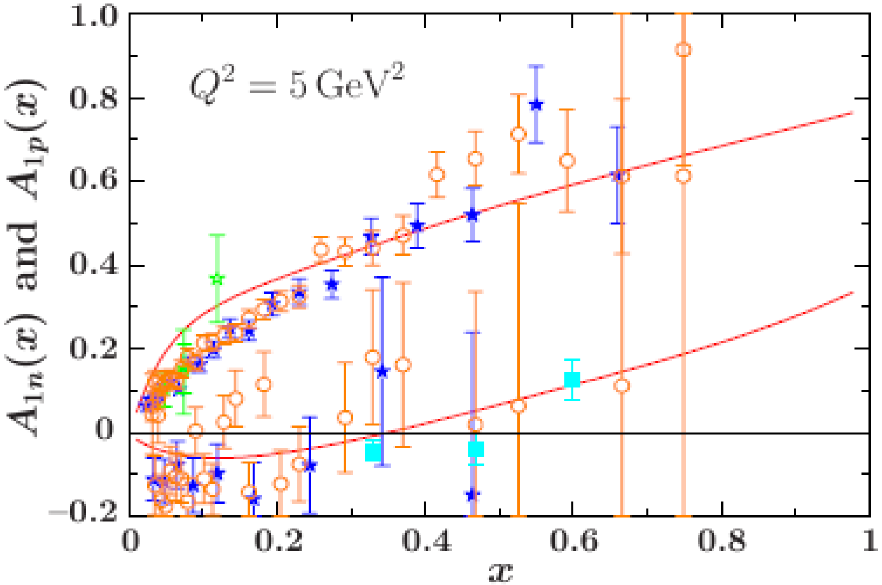
More Modern (Confining) NJL Calculations

Cloët et al.,
Phys. Lett. B621, 246 (2005)
(μ = 0.4 GeV)



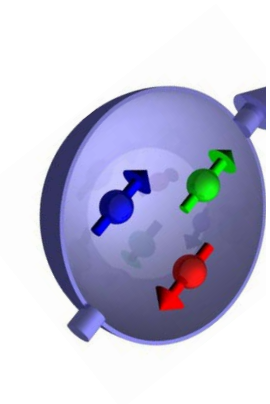


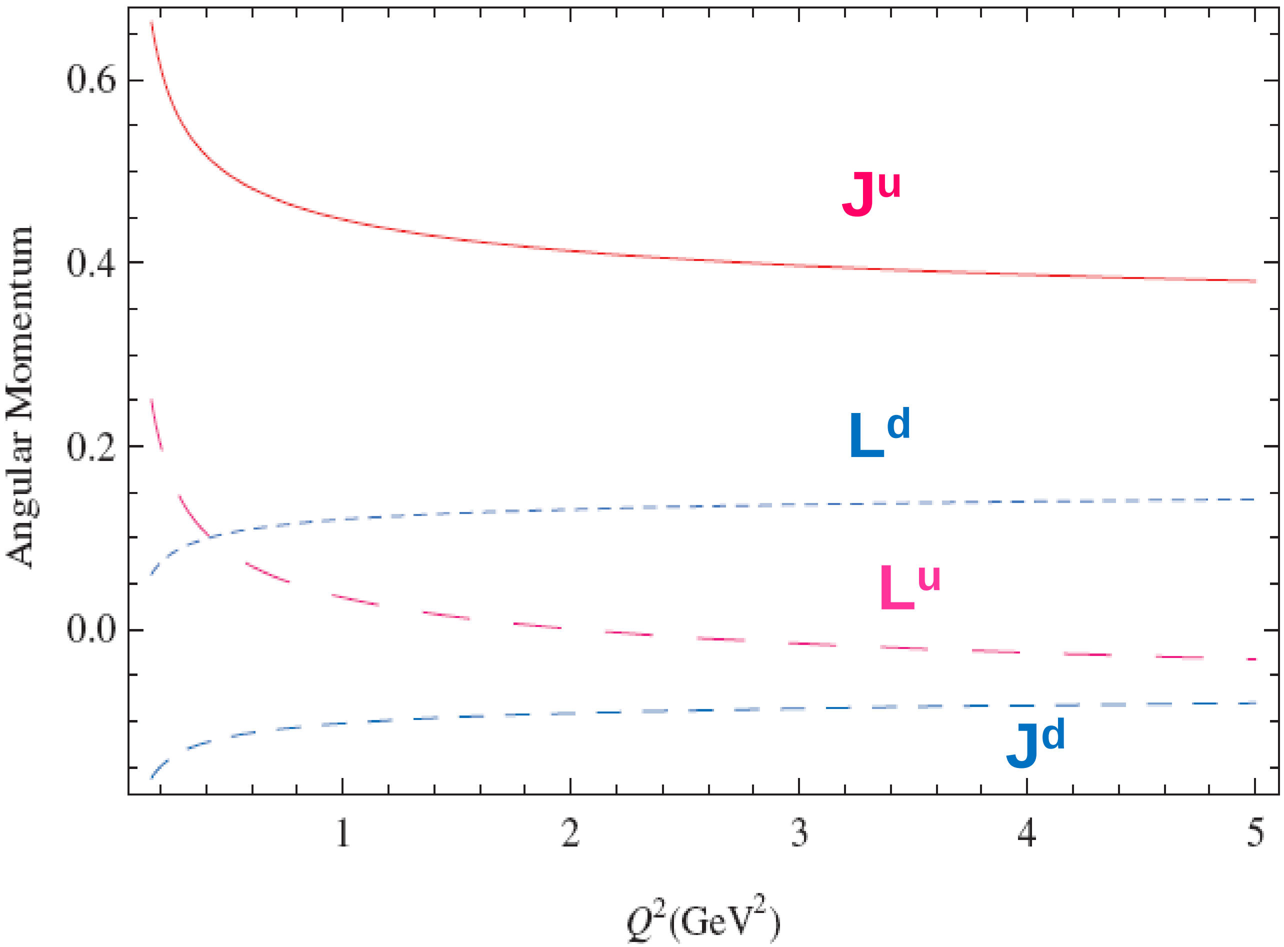


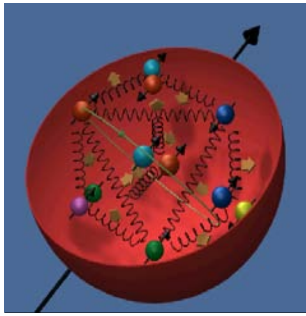
Solution of the LO Evolution Equations*

L^u and L^d both small and cross-over rapidly: AWT, PRL 101 (2008) 102003

- model independent !







Evolution equns: Ji, Tang, Hoodbhoy, PRL 76 (1996) 740

Update

- **Recently (Bass-AWT Phys Lett B684 (2010) 216)
  update to check g_A^8 and ensure that g_A^3 is correct**

- **g_A^8 = 0.46 ± 0.05 (not 0.57 : 20% SU(3) breaking)**

- **This implies that value of Σ extracted from experiment (needs g_A^8) should be 0.36 ± 0.03 ± 0.05**

- **To be compared with calculated Σ = 0.42 ± 0.07
  (no polarized gluon correction included)**

- **In this case we find: $J^{u,d,s}$ = (+0.66,−0.17, +0.01)
  at the model scale and $L^{u,d,s}$ = (+0.23, +0.045, +0.015)**

Modern value of Δs

- **The value suggested by the Bass-Thomas analysis (also 1989 work of Yamaguchi et al.) is Δs is between -0.01 and - 0.02**

- **Then Σ and g_A^8 differ by only ~ 0.06 (modulo minor effects of glue through the anomaly)**

- **Latest careful evaluation* of strange polarization in a careful lattice study of "disconnected" term, by**

Bali et al. [QCDSF], arXiv:1112.3324 ***indeed*** **yields**

$$\Delta s = -0.02 \pm 0.010 \pm 0.004 \text{ (MSbar at 7.4 GeV}^2\text{)}$$

***Essential to take into account flavor mixing – lattice artifact**

NLO Evolution – using Bass-Thomas update

Remarkable agreement between model and LQCD

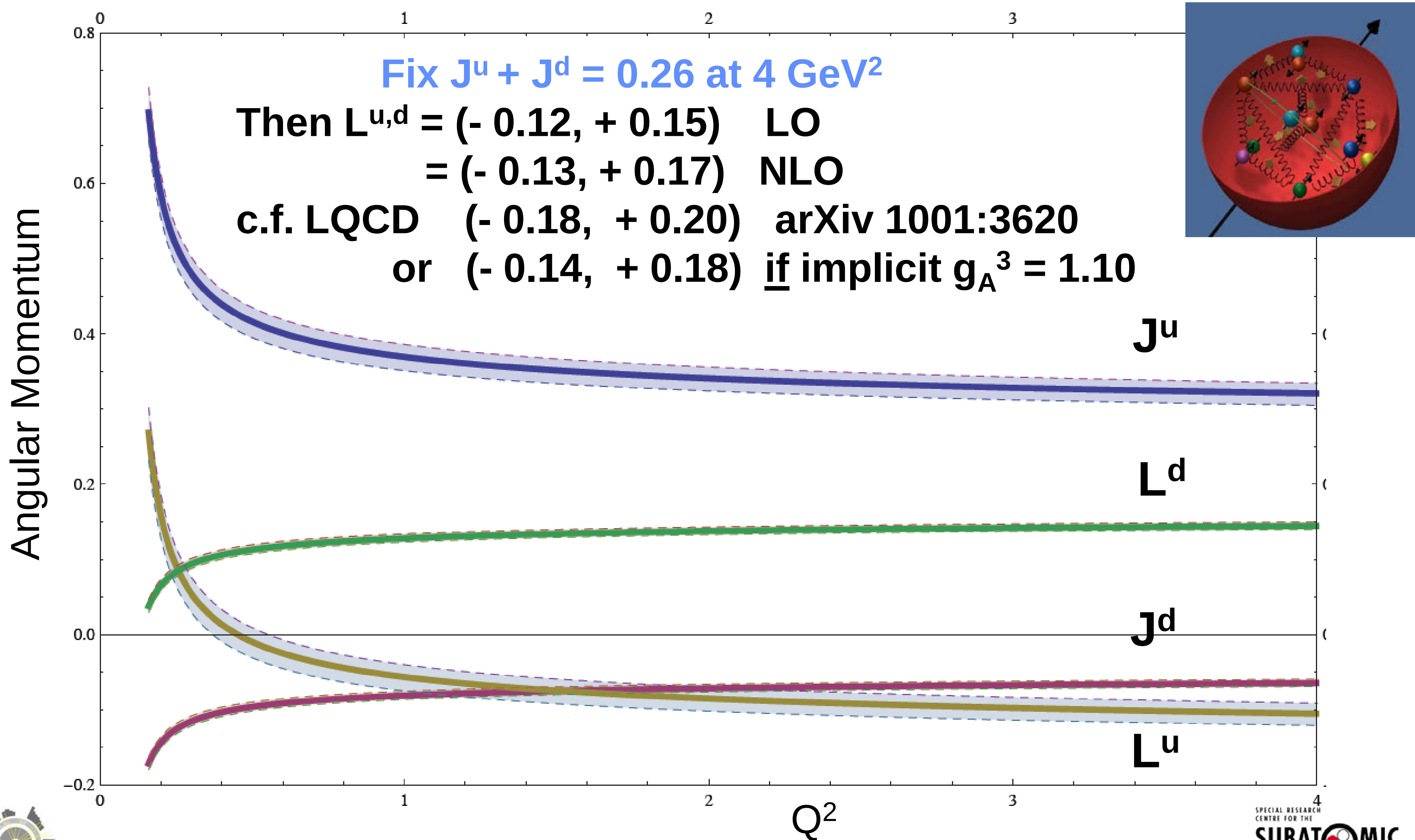
Fix $J^u + J^d = 0.26$ at 4 GeV^2

Then $L^{u,d}$ = (- 0.12, + 0.15) LO

= (- 0.13, + 0.17) NLO

c.f. LQCD (- 0.18, + 0.20) arXiv 1001:3620

or (- 0.14, + 0.18) <u>if</u> implicit $g_A{}^3 = 1.10$



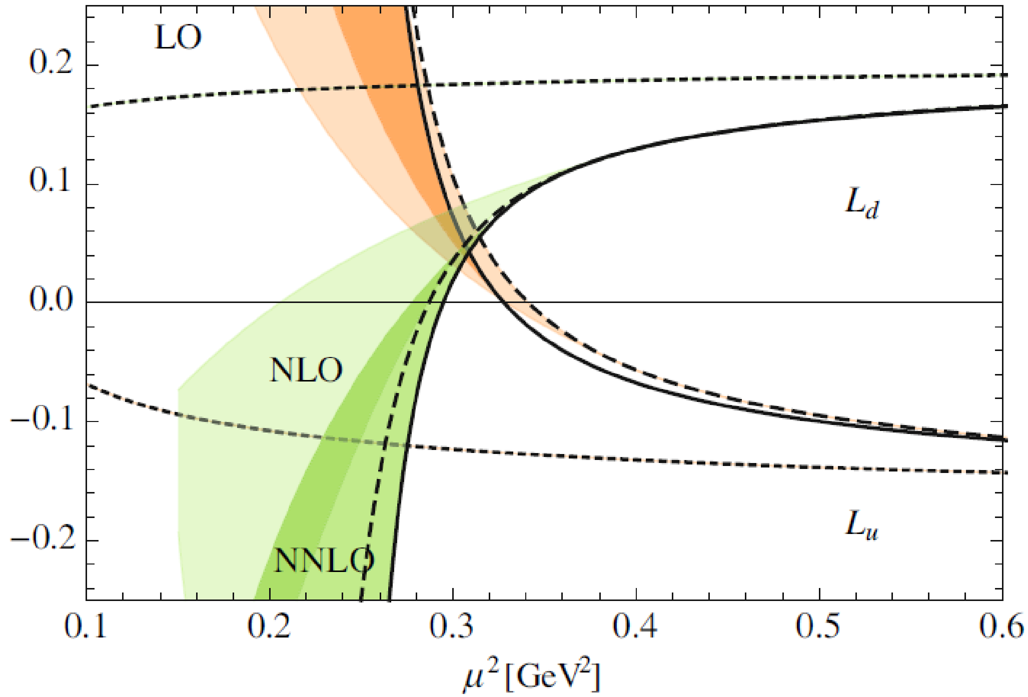
- Phys Lett 684 (2010) 216

& AWT, Casey & Matevosyan, E P J A46 (2010) 325

Similar study Altenbuchinger et al.

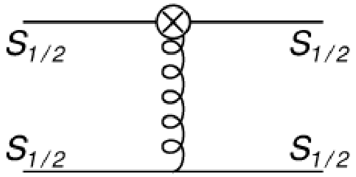
(EPJ : arXiv:1012.4409)

Report quite stable result for L^{u-d} under QCD evolution



N.B. These authors also pointed out additional correction for gauge invariant orbital angular momentum – important for L^q especially :

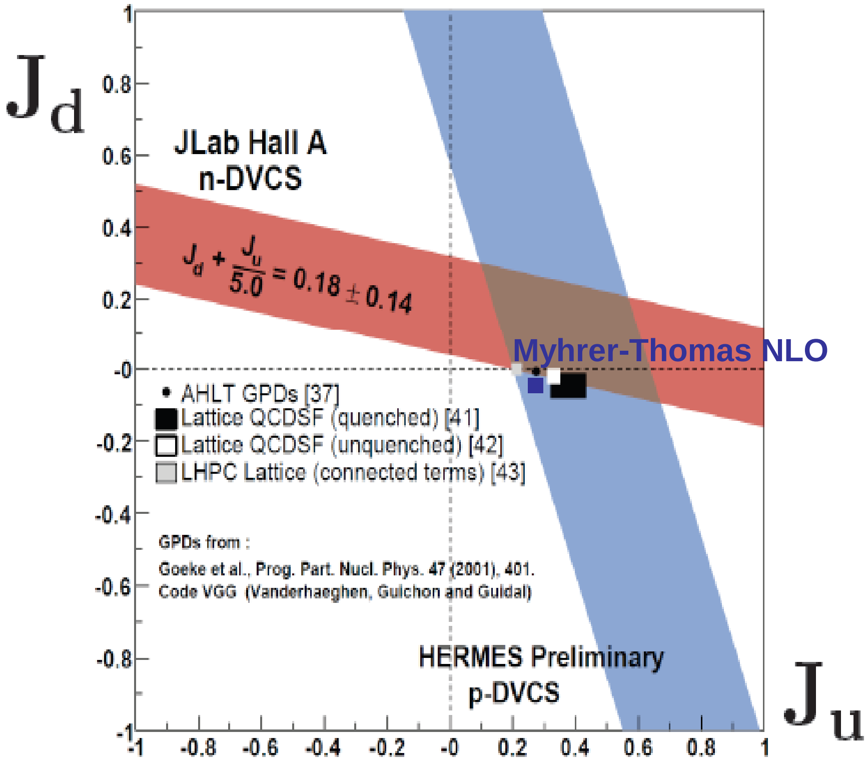
e.g. $L^q = 0.28 \rightarrow L^q_{GI} = 0.42$ ... with matching change in J^q

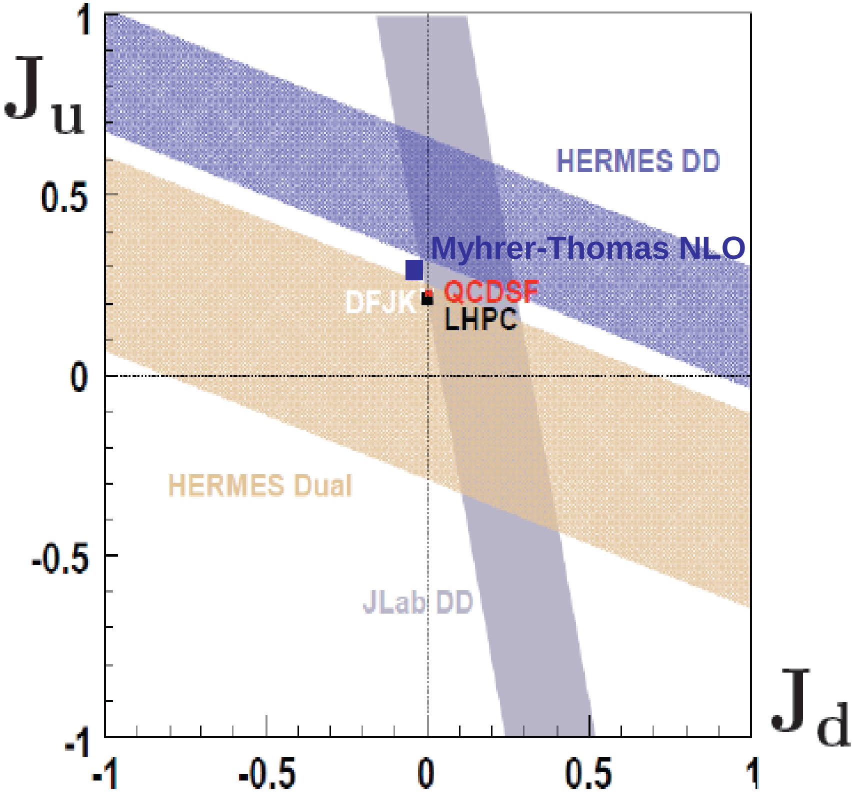


Experimental effort just beginning!

For the moment analysis highly model dependent ....

- ... from DVCS: (**JLAB** PRL 99 (2007) 242501 and **HERMES** JHEP 0806:066 (2008)





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Some Remaining Physics Issues

- **What control do we have over systematic errors in lattice QCD calculations?**

- **Especially: volume dependence**
  chiral extrapolation
  extrapolation in t

- **Recall: to determine L^q one subtracts Δq from J^q**

- **We know how hard it is to get g_A BUT the Q^2 dependence of g_A is off by a factor of two in state of the art simulations – where we *know* the answer**

- **There is no known control against which to judge the determination of $B_{20}(0)$**

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$L^{u\text{-}d}$ as example of physics significance

- **Wakamatsu and collaborators find $L^{u\text{-}d}$ fairly large and negative in χQSM** (Wakamatsu & Tsujimoto, P R D71 (2005) 074001)

- **Very similar to lattice results but model scale MUCH lower (~ 0.3 – 0.4 GeV^2 following Diakonov)**

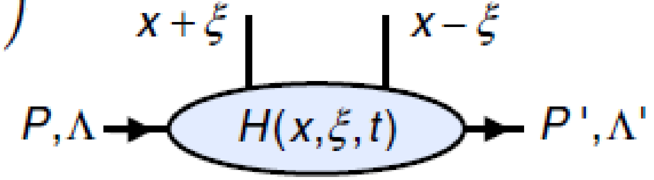
- **At LO :** $$L^{u-d}(t) + \frac{\Delta u - \Delta d}{2} = \left(\frac{t}{t_0}\right)^{-\frac{32}{9\beta_0}} \left(L^{u-d}(t_0) + \frac{\Delta u - \Delta d}{2}\right)$$
  and evolution is slow if $J^{u\text{-}d}$ (object in bracket) is small

- **Δu – Δd on right is whatever is implicit in lattice??**
  – BUT on left we usually use measured g_A !

- **Our NLO results and NLO and NNLO of Altenbuchinger *et al*. suggest that $L^{u\text{-}d}$ is most likely positive at a typical model scale....**

LQCD Calculation: e.g.Hägler et al. (LHPC)PR D77 094502

$$\mathcal{O}_{\Gamma}(x) = \int \frac{d\lambda}{4\pi} e^{i\lambda x} \bar{q}\left(\frac{-\lambda n}{2}\right) \Gamma \mathcal{P} e^{-ig\int_{-\lambda/2}^{\lambda/2} d\alpha n\cdot A(\alpha n)} q\left(\frac{\lambda n}{2}\right)$$



$$\langle P', \Lambda' | \mathcal{O}_{\not n}(x) | P, \Lambda \rangle = \langle\langle \not n \rangle\rangle H(x, \xi, t) + \frac{n_\mu \Delta_\nu}{2m} \times \langle\langle i\sigma^{\mu\nu} \rangle\rangle E(x, \xi, t),$$

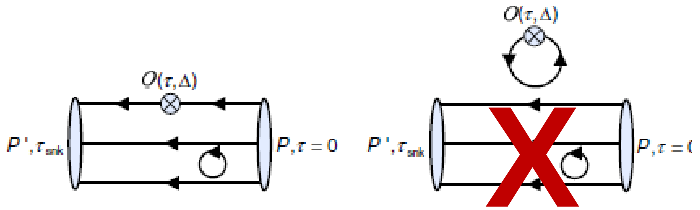
OPE :

$$\langle P' | \mathcal{O}^{\mu_1} | P \rangle = \langle\langle \gamma^{\mu_1} \rangle\rangle A_{10}(t) + \frac{i}{2m} \langle\langle \sigma^{\mu_1 \alpha} \rangle\rangle \Delta_\alpha B_{10}(t),$$

$$\langle P' | \mathcal{O}^{\{\mu_1 \mu_2\}} | P \rangle = \bar{P}^{\{\mu_1} \langle\langle \gamma^{\mu_2\}} \rangle\rangle A_{20}(t) + \frac{i}{2m} \bar{P}^{\{\mu_1} \langle\langle \sigma^{\mu_2\}\alpha} \rangle\rangle \Delta_\alpha B_{20}(t) + \frac{1}{m} \Delta^{\{\mu_1} \Delta^{\mu_2\}} C_{20}(t),$$

where: $\mathcal{O}^{\{\mu_1 \dots \mu_n\}}_{[\gamma_5]} = \bar{q}(0) \gamma^{\{\mu_1} [\gamma_5] i\overleftrightarrow{D}^{\mu 2} \cdots i\overleftrightarrow{D}^{\mu n\}} q(0)$

J^q = [$A_{20}(0)$ + $B_{20}(0)$] / 2

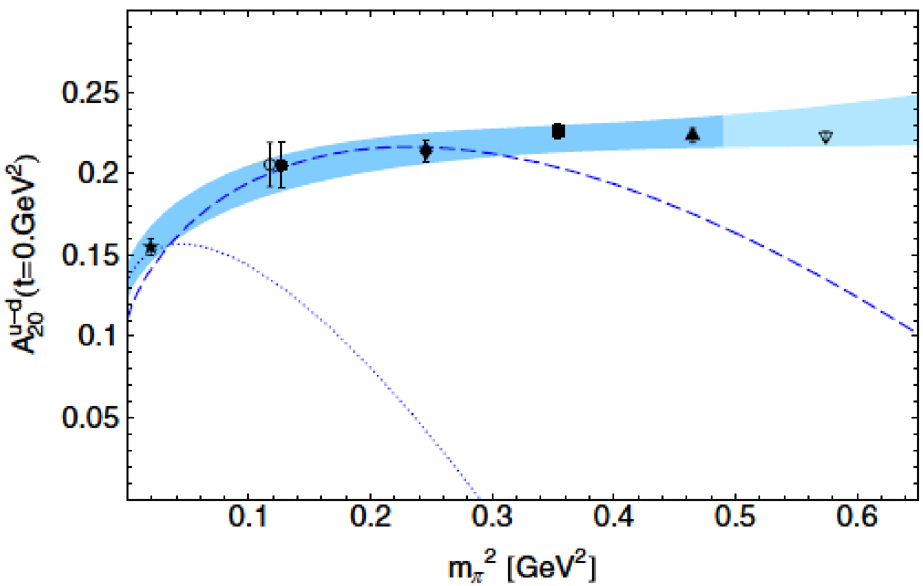


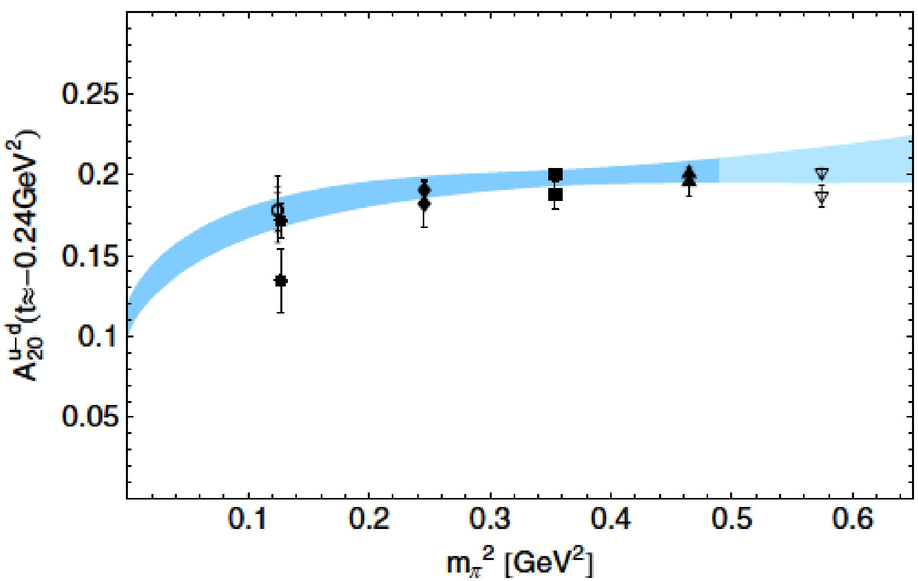
LQCD Needs Chiral Extrapolation and t → 0

Lattice groups typically use dim-reg over large range of m_π^2

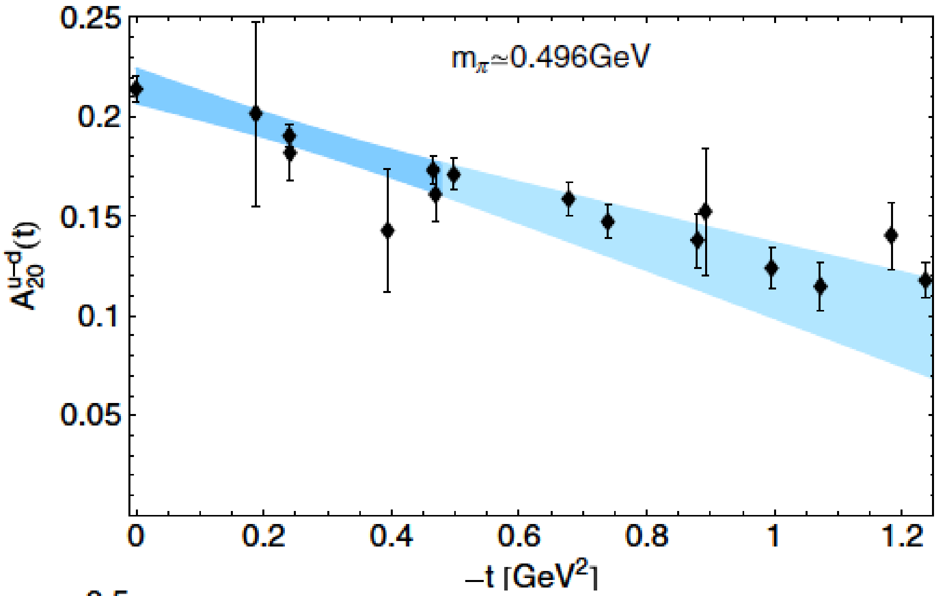
— we know this is beyond range of convergence and therefore suspect (prefer FRR)

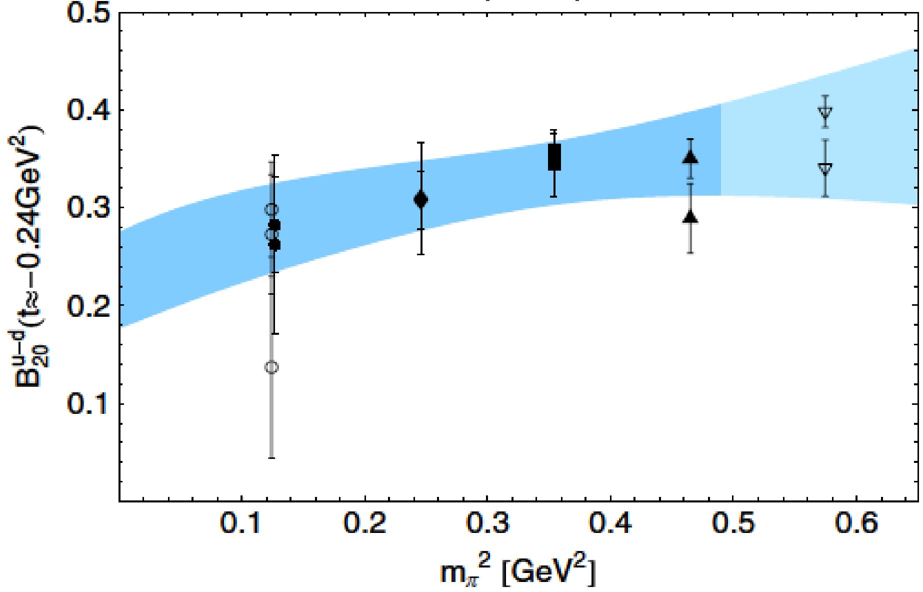
— also extrapolate B_{20} (t) *linearly* in t over (0,1.2) GeV^2





LHPC Results cont'.





Results:

$J^u - J^d = + 0.21 \pm 0.04$

$L^u - L^d = - 0.42 \pm 0.04$

$L^u = - 0.19 \pm 0.02$

$L^d = + 0.23 \pm 0.02$

(modulo disconnected terms)

- small errors rely on fit with low # parameters over huge range of t, m_π
- volume dependence taken to be small

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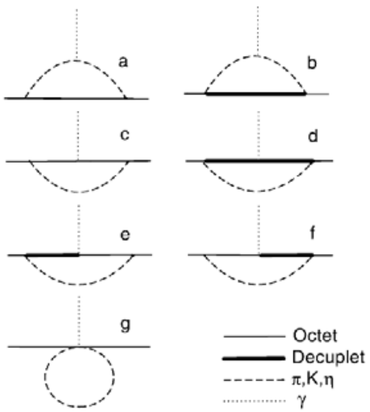
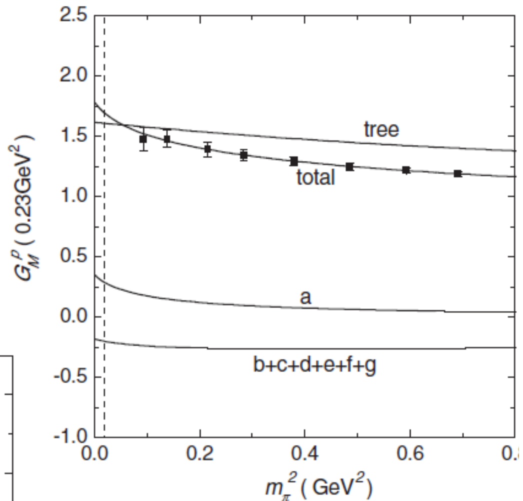
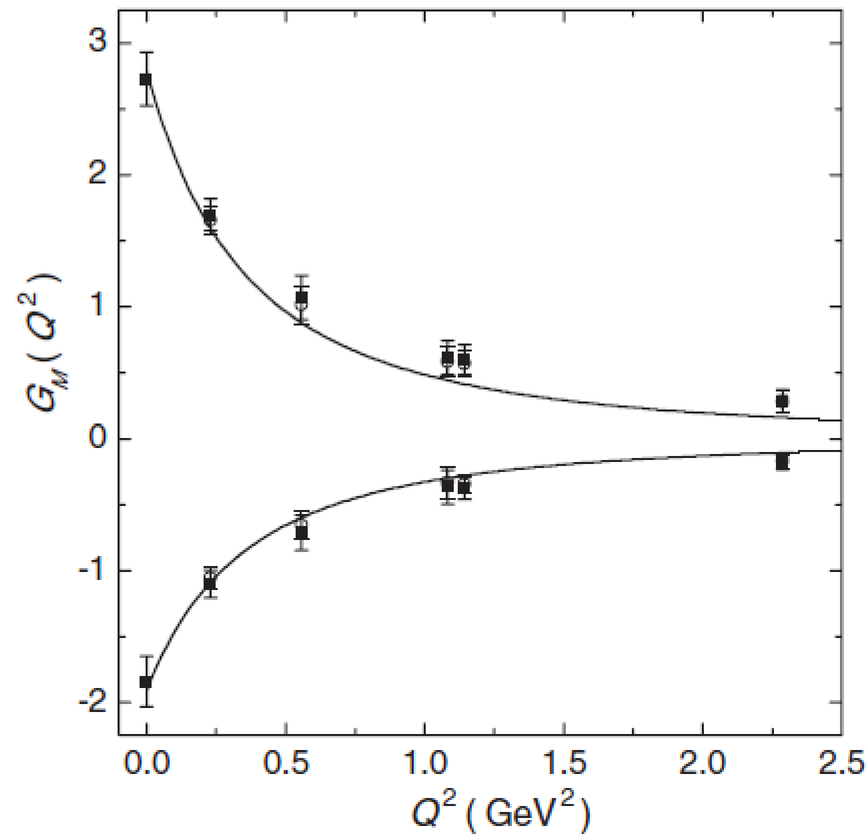
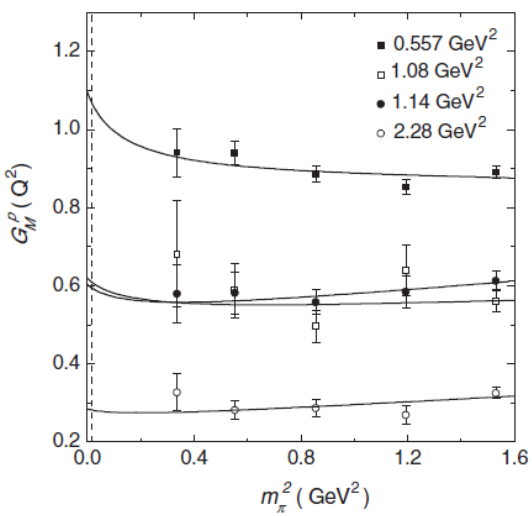
Check Using Finite Range Regulator

As in $G_M^s(Q^2)$ study of Wang et al., PR D75 (2007) 073012









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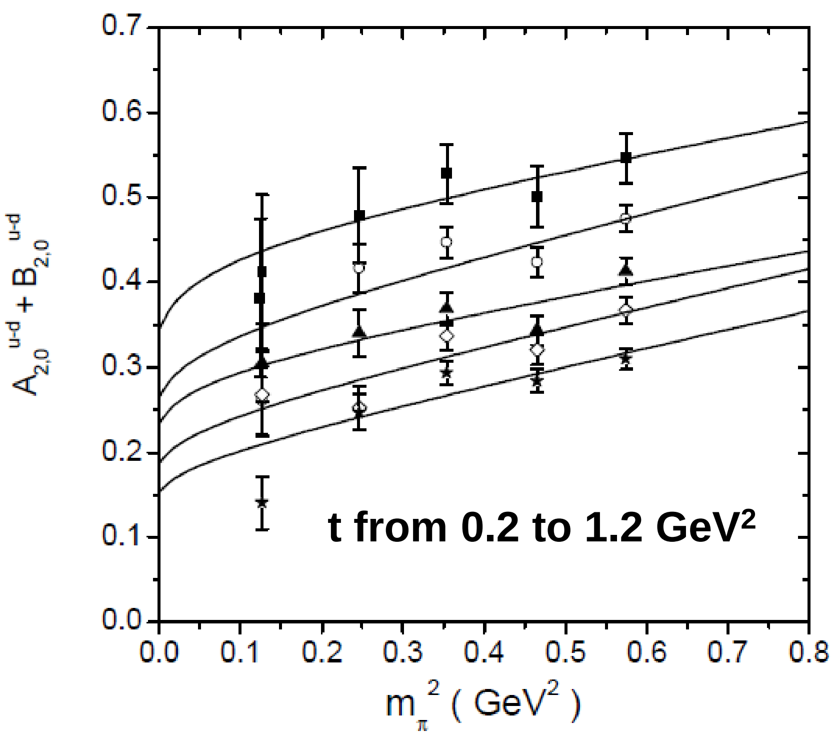
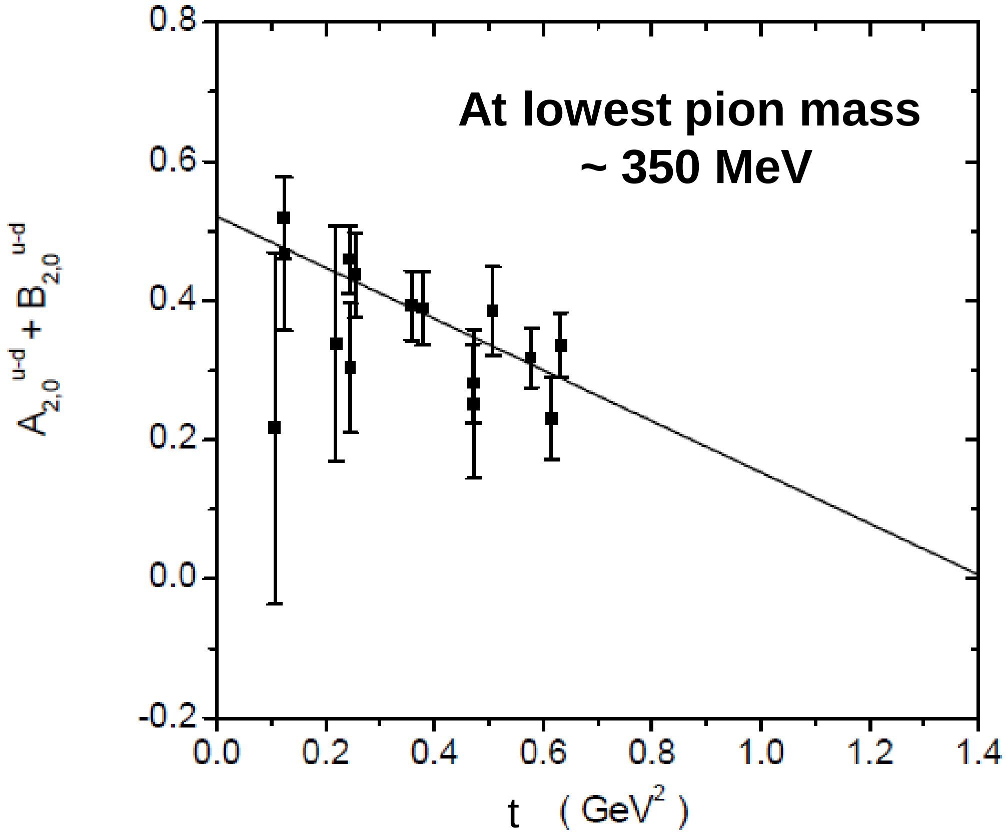
FRR Treatment of GPD moments*





Results similar to LHPC analysis
e.g. $J^u - J^d \sim 0.22$

BUT errors may be larger …

Also, extrapolation in t using a dipole rather than a linear function increases J^{u-d} by 25%

***Wang & Thomas, PR D81 (2010) 114015**

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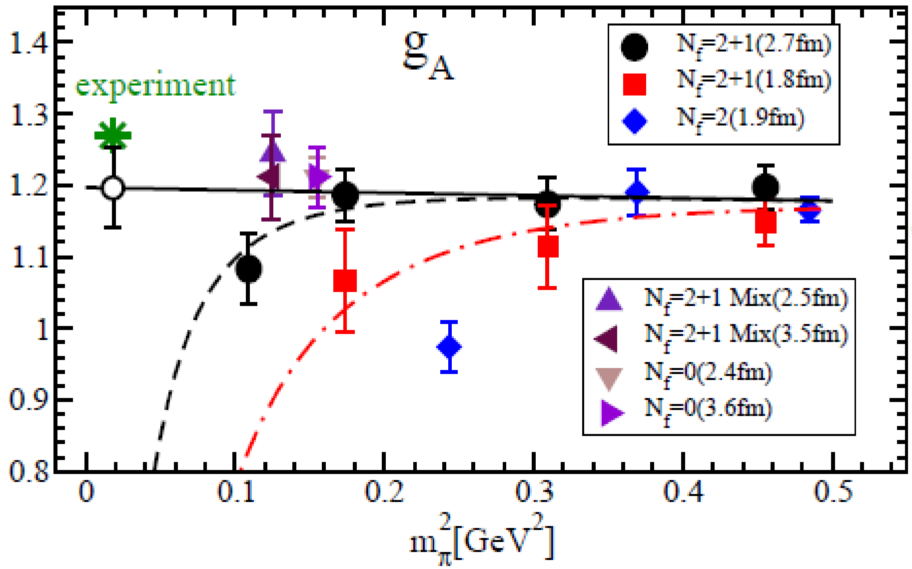
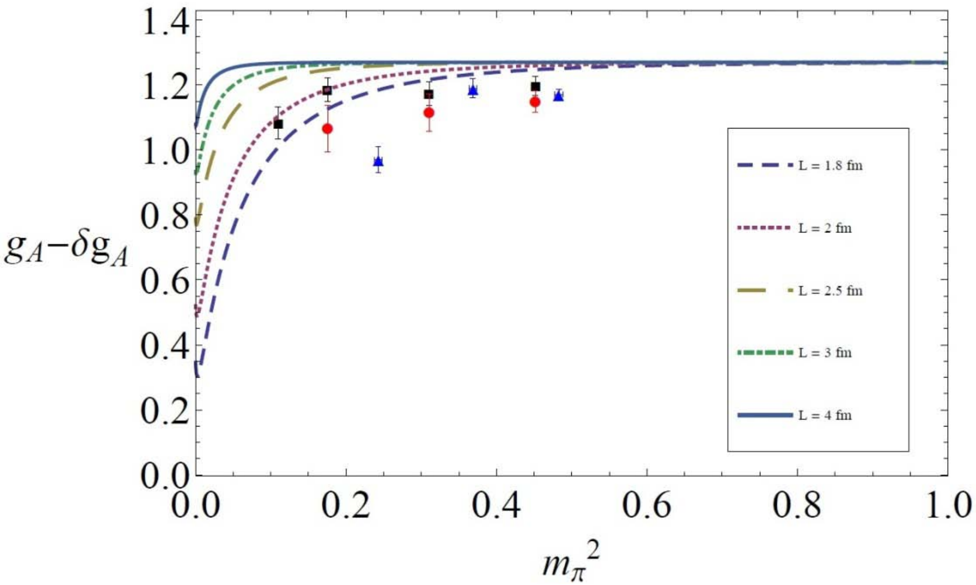
Volume Dependence of g_A Dramatic

- As well as $m_\pi \rightarrow m_\pi^{phys}$ and $t \rightarrow 0$, one has to deal with finite a and $L \rightarrow \infty$. Latter is especially problematic given that J^{u-d} includes some implicit $\Delta u - \Delta d$: while RBC-UKQCD studies have shown <u>strong</u> volume dependence for this

  \- no detailed study yet for GPDs



Yamazaki et al. [RBC + UKQCD] arXiv: 0801.4016

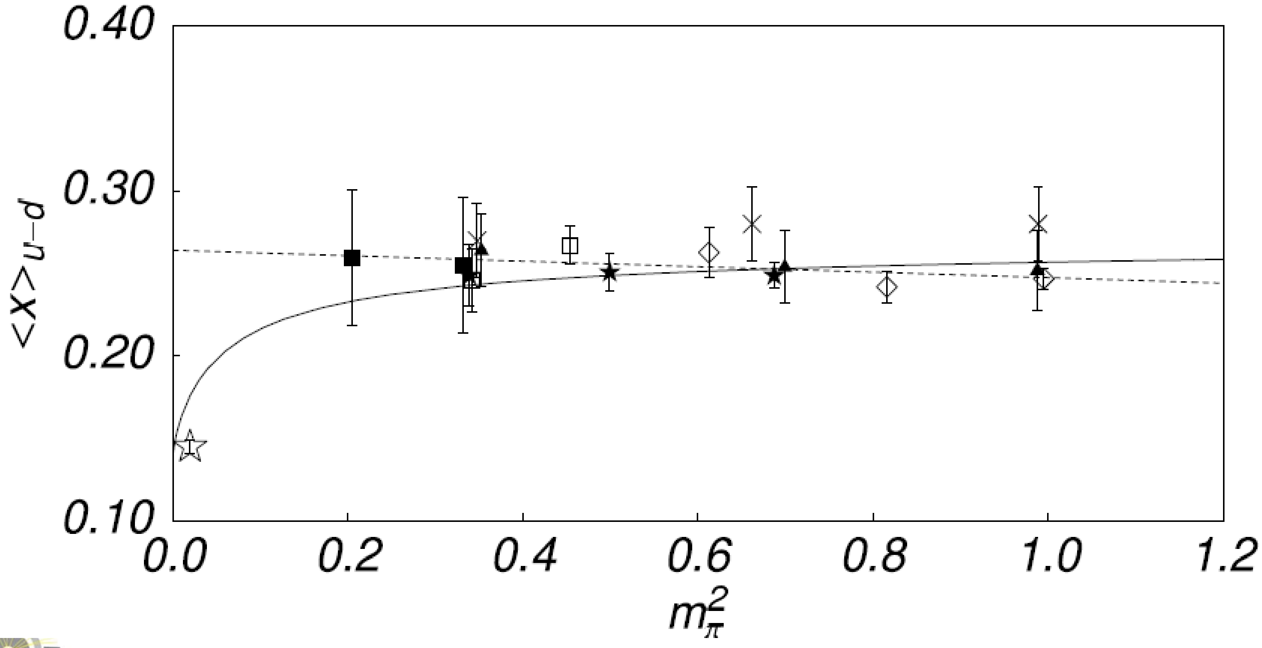


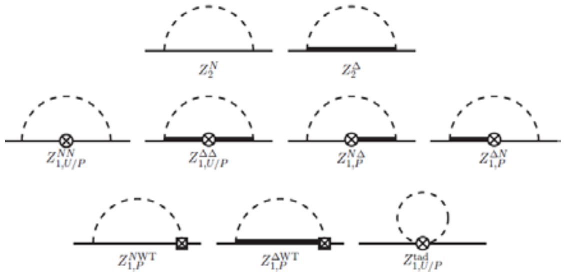
Hall, Young ,Thomas, in preparation

Chiral Corrections

- **Using expansions based on being in the power counting regime (very low pion mass) are very unreliable**

- **FRR works exceptionally well – a "model" but it's under control and yields stable, reliable results**
- **e.g. For <x>$_{u-d}$:** Detmold, Melnitchouk and AWT, PR D66 (2002) 054501





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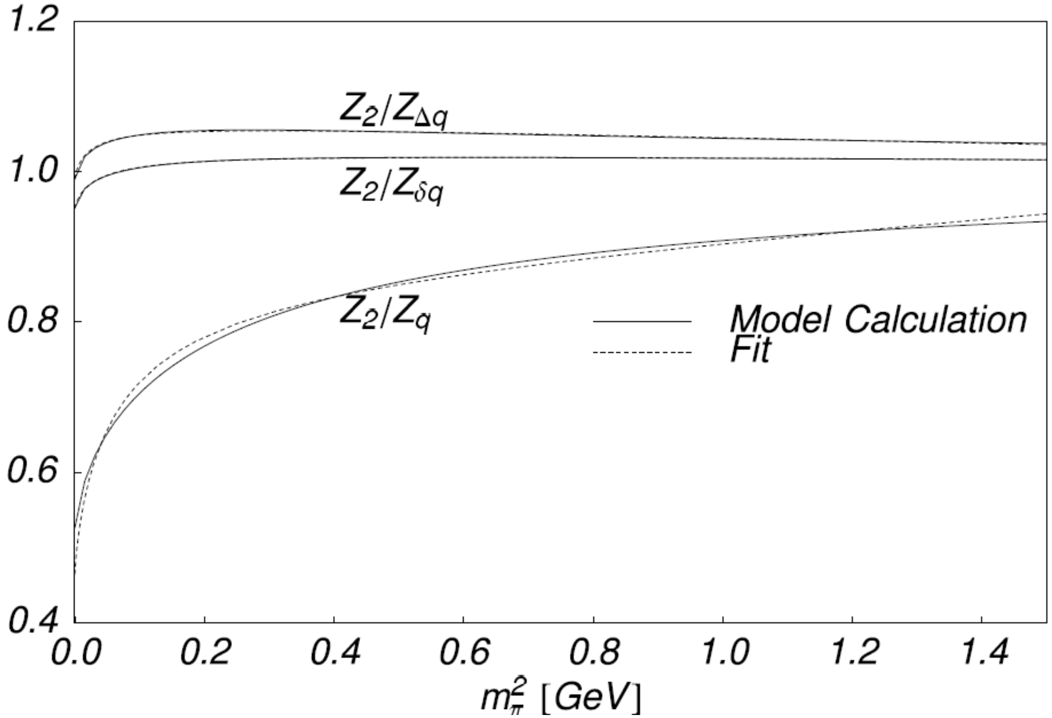
Extrapolation of <x>$_{u-d}$ and g_A



Finite	Volume	Correction
<x>$_{u-d}$	2.5fm	3.5fm
400 MeV	10%	0%
300 MeV	18%	5%
140 MeV	30%	12%

- **Fits to full FRR calculation use simple form:**

$$Z_2/Z_i = \alpha_i + \beta_i m_\pi^2 + \frac{\gamma_{i,\mathrm{LNA}}}{(4\pi f_\pi)^2} m_\pi^2 \log\left[\frac{m_\pi^2}{m_\pi^2+\mu_i^2}\right] , \qquad i = q, \Delta q, \delta q$$

  - **as in** Detmold et al., PRL 87 (2001) 172001 **where importance of the chiral extrapolation was first demonstrated for <x>$_{u-d}$**

Summary

- Two decades of experiments have given us important new insight into spin structure of the p

- U(1) axial anomaly appears to play little role in resolving the problem
  - not as severe as in original EMC paper

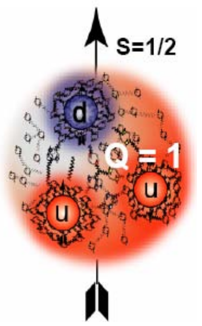
- Instead, important details of the non-perturbative structure of the nucleon DO resolve the "crisis"
  - OGE hyperfine interaction
  - chiral symmetry: pion cloud
  - relativistic motion of quarks

Ingredients of a minimal description of proton structure

Summary (cont.)

- **Important consequence for quark model:**
  a large fraction of the proton spin is carried as orbital angular momentum by valence quarks and by anti-quarks in the proton

- **Effect of QCD Evolution is to:**
  - flip ordering of L^u and L^d
  - reduce the size of orbital angular momentum
  - restore agreement between data,
  LQCD and the Myhrer-Thomas explanation



- **Study of GPDs at JLab at 12 GeV *may eventually***
  provide the primary tool to verify this
  (also transversity?)

Summary (cont.)

- For the time being lattice QCD offers the best hope of a determination of L^u and L^d

- However:
  - L^{u+d} uncertain: omission of disconnected terms;
  - L^{u-d} uncertain: need to extrapolate in t and m_π over large distance *and* need to subtract implicit value of g_A which may have significant finite volume errors

- For reasonable guess at finite volume effect L^{u-d} agrees very well with model of Myhrer and Thomas

- Much larger lattice volumes and smaller pion masses should resolve the problem – use FRR for extrapolation